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Uncalibrated Distortions vs Undersampling

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In a recent paper of ours [Hess & Field (1993). *Vision Research, 33*, 2663–2670], we claimed that there was a predictable relationship between position errors and contrast errors for an undersampled system. In this paper we re-state our main points. We feel that the response to that paper by Levi and Klein in the accompanying article does not require us to produce changes in our original position. We believe that the data support the notion that the principal causes of the positional errors in the normal periphery and in the amblyopic visual system are due to uncalibrated distortions in the local signs of visual neurons. We believe that undersampling plays a major role in producing positional errors only in the far periphery at, or very near, the acuity limit. We maintain that our initial studies provide strong evidence that undersampling is insufficient as an explanation for the positional errors in the periphery of normals (Hess & Field, 1993) or the central field of amblyopes [Hess & Field (1994). *Vision Research, 34*, 3397–3406. Copyright © 1996 Elsevier Science Ltd.

Amblyopia Spatial vision Periphery Distortions

INTRODUCTION

In a recent paper, we noted that the principle of univariance leads to a particular relation between contrast errors and position errors (Fig. 1 in Hess & Field, 1993) and we have shown that this relation does not appear to hold in either the peripheral field of normals (Hess & Field, 1993) or the central field of amblyopes (Hess & Field, 1994). From this we conclude that undersampling provides an insufficient explanation for the loss of spatial accuracy in these two situations.

To summarize our main points:

(1) Undersampling is insufficient to explain positional errors in amblyopia and the normal periphery: (a) undersampling does not predict the apparent independence of contrast errors and position errors; (b) undersampling does not predict the size of the distortions; (c) tests of aliasing (e.g. Anderson & Hess, 1990) suggest that undersampling is only evident at the acuity limit in the periphery of normals and amblyopes.

(2) To account for the large positional distortions we proposed a "disarray" model to handle the results following the original distortion model proposed by Hess (1980): (a) the model assumes that a significant proportion of the errors in position are due to an uncalibrated positional error associated with the "local sign" of the cortical projections from the amblyopic eye; (b) in amblyopes, it was proposed that the possible cause of this error, was that during development, the projections of the two eyes are not properly aligned. Therefore, the calibration which allows a registration of visual position, will only be correct for one of the two eyes.

UNDERSAMPLING

Consider the function shown below in the upper part of Fig. 1. This is a Gabor function which can be sampled at a number of discrete locations. Let us begin by sampling the pixel array along the lines proposed by Levi and Klein (1986). While such discrete sampling is not a proper model of post-receptoral sensory undersampling (as noted by Levi and Klein in their reply), nevertheless it will serve to demonstrate the trade-off between errors in contrast and position which forms the foundation of our "theory".

If we sample this stimulus at a finite number of points (shown by the vertical lines in the lower part of Fig. 1), then the location and amplitude of the function will vary depending on the positions of the samples. However, at no time are any of the sample amplitudes larger than the original stimulus. Thus, if the peak of the sub-sampled Gabor function is shifted from the center, the amplitude of the function must fall.

We are pleased that Levi and Klein have agreed to plot the data in the format that we originally proposed (see their Figs 1 and 3), which was derived from our plot as shown in Fig. 2. The figure demonstrates our main point that there is a clear trade-off between position and contrast errors for any Gabor function of size sigma. We

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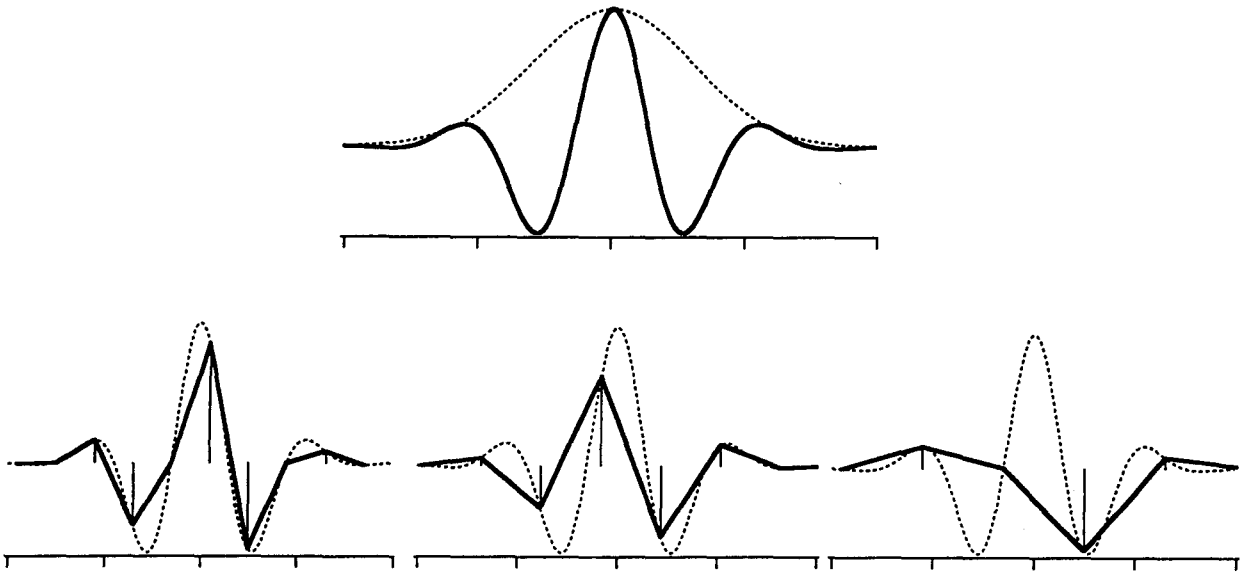

FIGURE 1. The figure demonstrates the results of undersampling with a Gabor function. The upper function is a Gabor function similar. If one samples this stimulus at discrete points, then both the position and the amplitude of the peak can vary. The solid lines show the sampled functions for three levels of undersampling. The peak of this sampled function can never be larger than that of the original function. Thus, for the Gabor function, the maximum amplitude of the peak falls when the position of the sampled peak varies off the center. In general, for a Gabor function, the envelope of the function defines the minimal contrast error for a given position error.

have marked the region of this graph relevant to Levi and Klein's (1986) pixel based (e.g. photoreceptor) undersampling model. It should be noted that while it is possible to have a larger contrast error than this curve, it is not possible to have a lower one. This curve is the same as that proposed by us in our original paper (Fig. 2—Hess & Field, 1993).

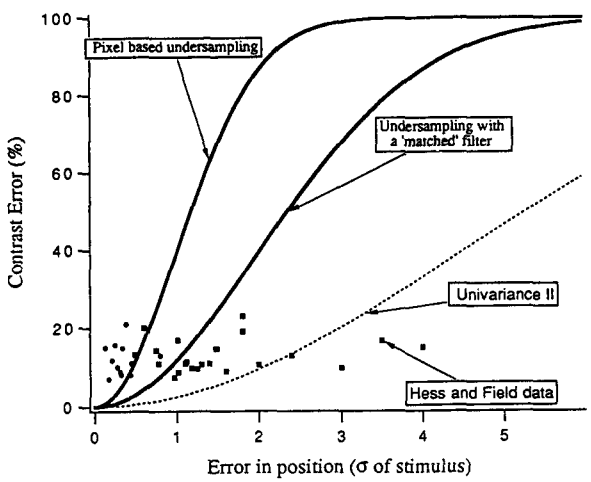

FIGURE 2. The figure shows the trade-off for the pixel-based undersampling of Levi and Klein as well as the predicted trade-off for undersampling when the Gabor stimulus is undersampled by an array of functions with similar bandwidth to the stimulus. The matched filter undersampling produces twice the positional error for a given contrast error but still results in a clear trade-off. Also shown is a plot of approximately the same Univariance II filter derived from Levi and Klein and shown in Fig. 3. The graph also shows the data of Hess and Field (1993) when the contrast errors are plotted in relation to the σ of the Gabor function stimulus. The fovea data are plotted as circles and the periphery data measured as various eccentricities are plotted as squares. As one can see, the data are not well predicted by any of the undersampling models.

Of course, pixel-based undersampling is not a reasonable description of post-receptoral undersampling in the visual system. As previously noted, it is more reasonable to assume that the undersampling occurs at a stage at which the band-pass filtering properties of neurons have to be taken into account. If we undersample with filters that have a spatial spread, then the trade-off shifts to the right. For example, a reasonable assumption is that a Gabor stimulus is detected by neurons with roughly the same receptive field profile. The convolution of a Gabor function with itself produces a function with twice the width and half the bandwidth. This shifts the trade-off relationship as shown by the line labeled matched filter in Fig. 2.

In all of these cases, there is a predictable trade-off between contrast errors and position errors. The curves show the minimal contrast error for a given position error. Larger contrast errors are possible, but not smaller ones. As we noted in our original paper, predictions of the exact relationship are difficult since they depend on the number and bandwidths of the mechanisms involved in detecting these stimuli as well as the degree of variability in the response of cells.

However, our results found no evidence for such a trade-off. In Fig. 2, we have re-plotted our results from the normal periphery in terms of the S.D. of the stimulus. One can see that under some conditions there exist relatively large errors in position, but that the contrast error remains around 15%.

Can these data be predicted by an undersampling model which assumes that the detector involved in

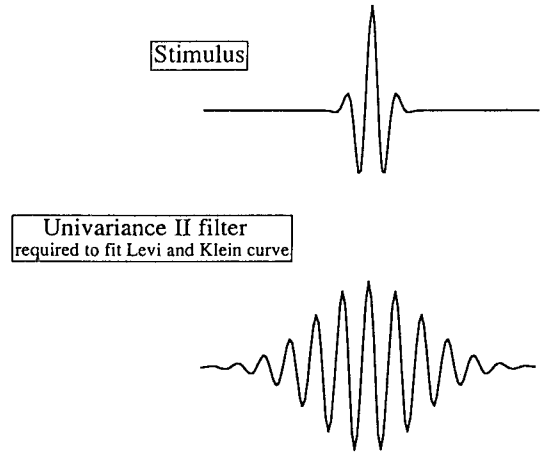

FIGURE 3. The top of the figure shows the stimulus. To produce the position errors shown in the dotted line in Fig. 2, one requires the filter to be tuned to the stimulus but to have a large receptive field, as shown. We do not feel that this is a reasonable model of the receptive fields involved in detection. However, even this model of undersampling does not produce the appropriate errors, as demonstrated in Fig. 2.

detection is much larger than the stimulus? This is essentially what Levi and Klein show in the plot they describe as "Univariance II". There are two problems with this model. First, the model still predicts a trade-off between contrast errors and position errors that are not found in the data. Second, since these results are obtained significantly below the acuity limit, this model predicts that the filter tuned to the stimulus must have a very large receptive field given its spatial frequency tuning. For a cell with a roughly linear spatial response (e.g. a cortical simple cell), the receptive field would need to be multi-lobed, as shown in Fig. 3. A plot of the trade-off with this Univariance II filter is shown by the dashed line in Fig. 2. The filter is 4× the sigma of the Gabor stimulus as required to produce a 50% contrast error when there are position errors of 5 × sigma. Even with a non-linearity like that produced by rectifying the output, the point is the same: the receptive field that is optimally tuned to the stimulus is required to be several times larger than the Gabor stimulus to produce the Univariance II curve. Furthermore, even if one was to accept that such an unusual filter was mediating detection, the model does not predict the lack of a trade-off shown in the data.

One might argue that a lower frequency receptive field will produce appropriate position errors without being multi-lobed. However, in such a case, the filter will not be tuned to the stimulus, thus creating large contrast errors because the cell is responding to the stimulus with the tails of the filter. The result would be to shift the entire curve up vertically, corresponding to the reduced response that the low frequency filters produce to the higher frequency stimulus. Again, this would provide a very poor match to the data.

We believe that these results support the notion that undersampling is insufficient as an explanation of positional errors in the normal periphery (Hess & Field, 1993). Our recent work (Hess & Field, 1994; Hess & Anderson, 1993) suggests that in amblyopia, undersampling is also an inadequate explanation for positional errors. An alternate explanation for the positional inaccuracy of both the normal periphery and the amblyopic central field is that there are positional distortions in the underlying neural array which limit performance. The notion that distortions in the underlying neural array may play a major role in amblyopia is not a new idea. This was first suggested by Hess *et al.* (1979) and led to the suggestion that "tarachopia" (distorted sight) rather than "amblyopia" (blunt sight) might be a more apt description of the condition (Hess, 1982). Hess *et al.* (1990) specifically proposed a theory of post-receptoral distortions and provided examples of how these distortions could be modeled.

OTHER POINTS

(1) The side issue of how best to plot our alignment data, whether it should be as a function of the eccentricity of our central stimulus or the eccentricity of the more peripheral stimulus, needs clarification. Since we used stimuli whose dimensions were scaled, the correspondence shown in Fig. 1 of Levi and Klein's letter could, in principle, be the result of either the change in size of the stimulus elements or the change in their separation (and hence the eccentricity of the most peripheral stimulus). The reader is referred to Fig. 5 of Hess and Hayes (1994) where it is shown that it is the stimulus size that matters and not, as Levi and Klein suppose, the eccentricity of the most peripheral element. Toet (1987) came to an identical conclusion (his Fig. 9, p. 330). As the eccentric location of the stimulus array becomes large compared with that of the element separation, this distinction becomes irrelevant.

(2) There is an interesting question of the sort of prediction that would be expected if the cortical neurons did not show the property of univariance. Indeed, as noted recently (Geisler & Albrecht, 1995), cortical neurons often show a significant breakdown in univariance. However, even if there is a complete breakdown in univariance (e.g. any stimulus falling within the receptive field of a cell has a known contrast), undersampling would not predict position errors larger than the receptive field size of the cell involved in the detection. Thus, the size of the errors as shown in Fig. 2 do not follow from undersampling even with a complete loss of univariance.

CONCLUSION

We stand by the logic of our original proposal. We maintain that the principle of univariance leads to predictions regarding the relation between position and contrast errors. Although the undersampling discussed by Levi and Klein appears to play an important role near the acuity limit in the normal periphery (Anderson & Hess, 1990), it does not provide a sufficient account of positional errors with stimuli either below the acuity limit in the periphery of normals or the central field of amblyopes.

Vernier tasks like those used by Levi and Klein (e.g. Levi *et al.*, 1985) may well involve cells with the smallest receptive fields near the acuity limit. Therefore, we do not question the possible role of undersampling with this task. However, below the acuity limit, where amblyopes commonly report visual distortions, we feel that the undersampling model is insufficient.

In our previous papers (Hess & Field, 1993, 1994), we introduced the idea that positional errors in these cases were due to a lack of "calibration" in the spatial array of cells covering the visual field. We believe that the resultant uncalibrated spatial distortions represent a useful model for the positional errors found in the periphery of normals and the central field of amblyopes.

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